LEWIS L. ORIARD, INC.

GEOTECHNICAL CONSULTING

3502 SAGAMORE DRIVE
HUNTINGTON BEACH, CALIFORNIA 92649

(714) 846-1515
or (714) 835-6886

REPORT OF INVESTIGATIONS

SEISMIC EFFECTS OF BLASTING OPERATIONS
OF
ANACONDA MINERALS COMPANY
ON
THE VILLAGE OF PAGUATE, NEW MEXICO

Prepared for

Anaconda Minerals Company
Grants, New Mexico

August 12, 1982

SEISMIC EFFECTS OF BLASTING OPERATIONS OF ANACONDA MINERALS COMPANY ON THE VILLAGE OF PAGUATE, NEW MEXICO.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

INTRODUCTION

In accord with the request of Anaconda Minerals, I have directed my attention to the question of blasting effects on the homes in Paguate, west and northwest of the past mining operations at the Jackpile, North Paguate and South Paguate mining areas.

I have discussed the past drilling and blasting practices at this site with Mr. Erwin Green of Anaconda, and have reviewed some of the company's records and files to acquaint myself with the operations. In addition, I have studied reports and data prepared by Mr. Philip Berger who was retained by Anaconda to monitor ground vibrations generated by the blasting operations.

In order to become familiar with the various repairs, remodeling and maintenance work done in Paguate by Anaconda over the years, I have met with Mr. Basil Ward and have spent some time with him in touring Paguate, at which time I observed the type of work his crews performed and the types of home construction to be found there.

I have also met with Mr. Fred Mirabal of Anaconda, have inspected the exterior of his home in San Rafael, and have viewed the general conditions of the buildings in San Rafael, an area far removed from any of the blasting activities.

In addition, I have driven through other villages and occupied areas in the region, and have studied files showing pre-blast inspections made of other, similar residences in New Mexico, as well as viewing miscellaneous commercial buildings in Albuquerque.

I have also studied the earthquake history of the region and have reviewed a summary of weather data.

The following is a brief summary of my observations and conclusions:

PRINCIPAL OBSERVATIONS

1. In Paguate, I did not find a correlation between building cracks and vibration intensity. I observed fewer cracks in the area near the blasting, and more cracks as I moved farther away from the blasting areas. Of course, this is the reverse of what one would expect to find if the blasting were to have caused the building cracks.

2. The cracks I observed in the buildings in Paguate are of the same type and character as those I observed in similar buildings in other areas where no blasting has taken place, such as in nearby villages, other occupied areas in the region, other areas around the United States, and in many foreign countries.

3. The conditions I observed were typical cases of damage and deterioration caused by static (non-vibratory) forces, such as shrinkage, expansion, settlement, temperature and humidity effects, water damage, age, and similar forces. Although I did not inspect every building in Paguate, and saw only the exteriors, I did not see any evidence of vibration damage. Rather a contrary correlation was shown, as stated in paragraph 1. Each type example I saw in Paguate can be found many times over in nearby areas where no blasting has taken place. These conditions are commonplace, not only in this area, but in most areas.

4. Many buildings in Paguate were given a pre-blast inspection, including photographic coverage, in 1961. The photographs serve to document the same conditions that can be seen today after the blasting operations have been closed down.

5. A portable seismograph was used to record the ground vibrations in and near Paguate for about 1400 to 1500 blasts during Anaconda's operations. None of the recorded vibrations was of sufficient intensity to cause structural damage to buildings.

PRINCIPAL CONCLUSIONS

Comparing the vibration data with what I observed of the homes in Paguate and with what information was given to me concerning these homes, my principal conclusions concerning blasting effects are these:

1. The blasting operations did not cause any structural damage to the homes in Paguate.

2. Over-all, the general condition of the village is better than it was before the mining operations began.

3. Anaconda has expended some 1 to 1¼ million dollars or more on the homes in Paguate. An inspection of Anaconda's records shows that a portion of these expenditures are identified as structural repair or repair of blast damage. However, a review of the type of work done and an inspection of the village show that this was merely a convenient way of categorizing alleged damage. The funds were spent largely on various

alterations, remodelings and improvements of a structural nature which are completely unrelated to the levels of vibration that were generated by the blasting operations. Further, the work done on these homes substantially increased the intrinsic values of the properties.

We can safely presume that something well in excess of $1 million has been spent to maintain good will and good public relations with the neighboring residents of Paguate, and not to repair blast damage.

4. On the other hand, the reactions of nearby residents has been perfectly normal and predictable. It would have been an extremely rare case if extensive damage claims had not been made, despite the lack of actual damage. The levels of vibration were well above those that are easily perceived by people, and it is a perfectly normal response for the average person to believe that motions which are so easily felt must cause damage. This sensitivity of people is the reason that pre-blast inspections are made and the reason that seismographs are used so extensively. If people were not more sensitive than the houses they occupy, there would be no need for these efforts because vibration specialists can provide safe guidelines without the inspections and without the seismographs.

BLASTING VIBRATIONS TRANSMITTED TO PAGUATE

During the life of the open-pit mining operations conducted by Anaconda, blasting took place at various locations within the three open-pit areas east-southeast of Paguate. The vibrations transmitted to Paguate during these operations were quite variable because of the variations in distance and in the blasting patterns. The minimum distance was approximately 1000 ft. to the nearest home and about 5000 ft. to the far side of the village. The more distant blasting took place at distances of the order of several miles.

One of the more important factors about ground vibrations generated by blasting operations is the manner in which these vibrations die out with distance. This diminishing of intensity is known as attenuation. The vibrations die out or attenuate in a regular manner which is easily calculated. Each time the distance from the blasting is doubled, the vibration is reduced to being about 1/3 as much as before. For example, at 2000 ft., the vibration is about 1/3 that which is found at 1000 ft. At 4000 ft., the vibration is about 1/9 that which is found at 1000 ft. At 8000 ft., the vibration is about 1/27 that which is found at 1000 ft.

This relationship between distance and vibration intensity is very important in analyzing the potential for damage, or in determining whether the observed building conditions could be related to blasting. There must be some reasonable relationship between the amount of damage that occurred and the amount of vibration that occurred. One very striking characteristic of blast damage is that it becomes dramatically more intense as we approach the blast area. Of course, that would have to be true because of the very great increase in the intensity of the vibration at the closer distance. A person who is familiar with the subject would know that if the vibration is sufficiently intense to cause damage at a distance of 1 mile, it would cause great destruction to similar buildings at a distance of only 1000 ft.

Vibration intensity for blasting is usually expressed in terms of "particle velocity", that is the velocity of a particle on the ground surface as the vibration wave passes. During blasting operations such as those conducted in this case, the ground surface undergoes a small movement up and down, back and forth, and comes to rest exactly where it started. How fast this movement takes place is a measure of the vibration intensity and helps us determine whether or not the vibration is capable of causing damage to buildings. In the United States, it is customary to measure particle velocity in inches per second, and I will use those units in discussing the vibrations in this case. In other countries, it is more common to use metric units rather than English units. Today, most of the regulations, codes, laws and project specifications which govern blasting vibrations do so by limiting them in terms of particle velocity, though some include references to other characteristics of vibration.

Instruments can be designed to measure either the displacement, velocity or acceleration developed by a vibration. On this project, the portable seismograph that was used to record the vibrations did so by producing a permanent photographic recording of the displacement and the frequency of the vibration. From this, the particle velocity was calculated directly.

For those who may have heard some reference to the velocity of seismic waves, it is important to understand that particle velocity is a different item than the transmission velocity of a wave passing through the area. The wave will have the same transmission velocity whether of high or low intensity. The transmission velocity is not changed by the intensity of the wave, but is determined by the nature of the material through which the wave passes. It is different for air, water and rock, for example. On the other hand, the particle velocity is determined by the intensity of the wave. For example, a loud sound and a very quiet sound have the same transmission velocity, but a loud sound has a higher particle velocity.

The particle velocity of a ground vibration is a combination of how far the ground moves (its displacement) and the frequency of the motion (how many times it moves through a cycle in one second of time). A typical vibration for the case we are discussing here had a displacement in the range of several thousandths of an inch (about the thickness of a sheet of typing paper) and a frequency of several cycles per second.

A Sprengnether portable seismograph was used to monitor the blasting operations. At various times, the seismograph was placed at any one of about a dozen monitoring locations in the village, or southeast of the village closer to the mining operations. The seismograph was set out for 1400 to 1500 blasts. It was sometimes difficult for the seismograph operator to know precisely when a blast would detonate, and a few of these blasts were missed. About 1400 recordings were obtained. From a review of the data, a selection was made of the fourteen strongest vibration events recorded during the mining operations. Ten of the fourteen strongest vibrations were recorded on the old road near the mine. This road was later removed by the advancing mining operations. When these ten recordings are adjusted for the additional distance to the village, it is noted that the vibrations actually transmitted to the village by these ten blasts were not of any significance, ranging from only about 0.3 to 0.5 in./sec. at the closest house to about 0.07 to 0.08 in./sec. on the far side of the village.

The remaining four strongest vibrations were noted as follows:

Shot No. 75	11/3/67	0.65 in./sec. at Hershey's (1600 ft.)
Shot No. 143	6/11/68	1.36 in./sec. at Hershey's (1674 ft.)
Shot No. 217	10/24/68	0.56 in./sec. at Hershey's (2198 ft.)
Shot No. 429	9/13/69	0.49 in./sec. at O'Brian's (2957 ft.)

For purposes of comparison and discussion, let us calculate the vibration intensity at the near side and the far side of the village for each of these four shots, and then arrange them in order from the strongest downward:

	NEAR SIDE OF VILLAGE	FAR SIDE OF VILLAGE
1. Shot No. 143	1.36 in./sec.	0.19 in./sec.
2. Shot No. 429	0.66 in./sec.	0.14 in./sec.
3. Shot No. 75	0.65 in./sec.	0.09 in./sec.
4. Shot No. 217	0.56 in./sec.	0.11 in./sec.

These four shots are the only ones we need to discuss in detail in relationship to safe limits for buildings. As far as can be determined, the remaining shots fell below these values and would not be of interest.

None of these vibrations exceeded the recognized standard in effect at that time, and stayed well below the recommendations of Anaconda's vibration monitoring consultants. That standard was a peak particle velocity of 2.0 in./sec. That limit was used almost universally from about 1949 until about 1977. It is still in effect in many project specifications whose primary purpose is to avoid damage to residences. Since 1949, millions of blasts have been monitored and regulated by that standard, and observed by many researchers, consultants and other professionals.

That standard was intended to prevent damage to buildings in poor condition, but did not give any special consideration to people (who are far more sensitive to sounds and vibrations than are the buildings they occupy). In recent years, more and more consideration has been given to the comfort and the peace of mind of people, and more severe restrictions have been placed on sources of sound and vibration. For example, from 1977, the federal Office of Surface Mining has required that open-pit coal mines restrict their blasting so as not to subject adjacent homes to particle velocities in excess of 1.0 in./sec. Most professionals agree that this is a reasonable restriction for a long-term large-scale blasting operation. Higher levels on a long-term basis would be alarming to most people and might have the potential for eventually causing threshold cosmetic damage in poorly constructed homes. This is not to be confused with <u>structural</u> damage, which requires much stronger vibrations (see Dick, Richard A., "A Review of the Federal Surface Coal Mine Blasting Regulations", Proceedings of the 5th Conference on Explosives and Blasting Technique, St. Louis, Mo., 1979.) Low-frequency vibrations in excess of 1.0 in./sec. have a low probability of causing threshold cosmetic damage in a low percentage of poorly constructed houses. Such threshold cosmetic damage is of no structural consequence, and would not usually be detected by an occupant, as it would usually require a carefully conducted professional survey before and after blasting to determine that it had occurred.

Thus, even though more recent regulations have required open-pit coal mines to restrict blasting vibrations to much lower levels than was the case before 1977, and even though Anaconda's metal mining operations are not under the jurisdiction of the Office of Surface Mining, their blasting operations conformed to the more recent limits imposed by OSM, with the exception of only 1 event out of 1400. To put this into perspective, most professionals agree that 90% conformance is expected, and that the exceptions should not exceed 150% of the limit imposed. These criteria were easily met.

The conclusions drawn from this analysis of the vibration recordings in and around Paguate are as follows:

1. None of the vibrations exceeded the standard limit in effect at that time.

2. None of the vibrations exceeded the limit recommended by Anaconda's vibration monitoring consultants.

3. Even though the Office of Surface Mining has required that this limit be reduced to only 1.0 in./sec. since 1977, and even though OSM has jurisdiction over open-pit coal mines only, Anaconda's blasting operations conformed to these more recent recommendations, within the normal meaning of such conformance for blasting.

4. Only a few of the closest houses near the east side of the village received vibration intensities in excess of 1.0 in./sec. and this happened only once out of 1400 recordings. The remaining houses received particle velocities ranging from 1.0 in./sec. to 0.19 in./sec. for this one strongest blast, and far less for the vast majority of the blasts.

5. Not even the strongest single blast of the 1400 recorded was capable of causing structural damage.

EFFECTS OF NATURAL FORCES ON THE HOMES AT PAGUATE

In order to understand fully the reasons for building conditions at any particular locality, one would have to be aware of the natural forces at work, as well as the type of construction. Some of the natural forces at work in this region are (1) earthquakes, (2) freezing and thawing, (3) total temperature cycle and thermal stress, (4) rainfall, saturation and erosion, (5) humidity changes and absorption, and (6) wind and storm.

A full discussion of these many topics would be prohibitively lengthy. Therefore, only a few general comments will be made in order to acquaint the reader with some of the considerations.

Earthquake Vibrations at Paguate. The following references have been reviewed in order to make an estimate of ground motions that have been transmitted to the village of Paguate during earthquakes.

1. "Seismicity of the Rio Grande Rift in New Mexico", New Mexico State Bureau of Mines and Mineral Resources, Circular 120, 1972, by Sanford et al.

2. "Instrumental Study of New Mexico Earthquakes, January 1968 Through June 1971", New Mexico State Bureau of Mines and Mineral Resources, Circular 126, 1972, by Toppozada, T.R. and Sanford, A.R.

3. "Earthquakes in New Mexico, 1849-1977", New Mexico Bureau of Mines and Mineral Resources, Circular 171, Sanford et al.

4. "Earthquakes in New Mexico, 1978-1980, Chapter 3, Updating of New Mexico Seismic Data", New Mexico Tech. Report prepared for DOE Low Temperature Assessment Program, 1981, Sanford et al.

As far as I am able to determine, no monitoring instruments were stationed in Paguate to record earthquakes. However, we can calculate the probable ground motions from the reported data and thus make a reasonable estimate of the vibration intensities in Paguate during these earthquakes. Referring to some of the earthquake data before 1962, we see that an Intensity of about IV (Modified Mercalli) would be estimated for Paguate, generating a particle velocity of about 0.63 in./sec. throughout the village. This motion would have been stronger for the majority of homes in Paguate than that induced by the blasting operations, although several of the closest homes to the mine received stronger motion from the blasting on one occasion.

There would be no reason to expect that any damage was caused by these earthquakes, considering the modest levels of vibration. However, as a matter of secondary interest, it should be noted that earthquakes can be expected to continue into perpetuity in this region, whereas the blasting operations have been terminated.

Temperature Effects. A review of weather records for this region shows that the annual range of temperatures typically is of the order of 100° F, with a maximum range of about 118° F sometimes occurring (from 16° below zero to 102° above zero).

Such temperature changes introduce very large stresses and strains in construction materials and in buildings. Even if freezing never occurred, the shrinkage and expansion associated with such temperature changes is damaging, and becomes more so for buildings where different materials are in contact (differential stress).

When the temperature drops below freezing, the damage is compounded. Materials which are not subject to freezing, and do not contain moisture will shrink as the temperature drops. Those materials which contain moisture will expand upon freezing, and will do so differentially because the freezing generally is confined to the near-surface zones. These natural forces are very damaging. In addition to the direct impact they have on the building itself, they adversely affect the soils and the foundations beneath the buildings, often causing pronounced swelling in the frozen state, then settlement when the thaw occurs.

Moisture Absorption. The area is relatively dry on a long-term basis, being subject to an average rainfall of about 10 inches (there was a maximum of 15.4 inches in 1969). However, occasional heavy rains are potentially very damaging to adobe construction. Even elevated humidity causes swelling of adobe, whether in the form of rain or not. Even if the adobe is not eroded by direct contact with the rain, adobe brick and adobe mortar can undergo dramatic changes in dimension with changes in moisture content simply by absorbing moisture from the air. The effect is proportionately worse as the clay content of the adobe

ases. Conversely, heavy shrinkage occurs when a

Moisture changes have similarly adverse affects on clay foundation soils beneath structures. Severe structural damage can be expected when buildings are supported by expansive soils.

Wind. Wind damage is more easily identified since it happens quickly at a time when observers are aware of the force and can watch it at work. Many of the other natural forces work slowly and quietly and are unknown to the building occupants. The most common wind damage is that to windows or roofs, although violent winds can cause even more severe damage.

The continuous pressure of a wind has more capability of causing damage, such as the breaking of windows, than would the highly transient (short duration) pressure of an air wave from blasting, even though they might be at the same pressure. For example, if an engineer were selecting window glass to resist a certain pressure, he would select a stronger window if the pressure were a steady pressure such as wind, and he could select a thinner, weaker window if the pressure were transient, such as that from a sonic boom or a blast.

To give the reader some idea of the relative pressures involved, a typical surface mine blast would generate an air pulse which would have a pressure equivalent to a breeze of about 10 to 15 miles per hour.

HUMAN RESPONSE TO BLASTING EFFECTS

Upon hearing the startling secondary sounds often associated with blasting, such as rattling windows or doors, or the impact type of sound generated by an air wave against the roof or walls, etc., an observer will often judge that such sounds could only occur if something potentially harmful were taking place. And, indeed, the sounds might be identical if something harmful were taking place. Typically, the observer will then examine the house carefully and, of course, will discover certain cracks and other defects because these things exist in every house. Very often, such a person will then be genuinely convinced that blast damage has indeed occurred. He is not aware of the normal static (non-vibratory) forces which act on structures and bring about their typical condition.

One of the earliest studies of human response to motion was made by Reiher and Meister in 1931. Human subjects were tested for their response to steady-state vibrations in a 4 foot x 6 foot freely suspended platform. Among other things, it was observed that a standing person is more sensitive to vertical motion, and that a person lying down is more sensitive to horizontal motion perpendicular to the long axis of his body. All subjects were easily able to notice a motion which would be only about 1/100 of a potentially harmful level for structures.

Crandell (1949) reviewed this data and summarized his conclusions regarding the response of humans compared to that of structures. He concluded that the average person would consider a vibration to be "severe" at about 1/5 of the level that might damage structures. A great deal more data has been gathered in the ensuing years, confirming some of these basic observations, and adding certain refinements.

In the frequency range of typical blast vibrations of very short duration, the threshold of perceptibility to the motion does not appear to vary much with frequency, but it does vary considerably between individuals. In the case of small blasts, it varies considerably with duration. Although time dependence seems evident to an experienced observer of blasting phenomena, a quantitative relationship has not yet been established by controlled experiment. Moreover, such experiments would not be especially fruitful in the solution of blasting problems because other complex factors accompany the judgment of the observer. However, the results of tests with steady-state vibrations are of some benefit to the inexperienced observer. With motion alone, the results of experiments in response to steady-state vibrations are somewhat conservative. Depending on time duration of the transient vibration, the response may vary from about one-half of the response level to steady-state vibrations up to a level about equal with that to steady-state vibrations.

Thus, people are about half as sensitive to a motion of very short duration as to a steady-state motion, if the motion is not accompanied by sounds or other effects that could influence the human physiological or psychological response.

An objective response of a volunteer human to soundless, steady-state motion is not of sufficient help to explain the apparent extremes of sensitiviy exhibited by subjective homeowners responding to both motion and sound effects in their own homes from nearby blasting operations.

In actual practice, all rules for predicting motion response fall apart when sound effects accompany the motion and the motion is of short duration. In such instances, the average person forms a judgment based largely on his psycho-acoustic responses and is usually unaware of the important distinction between the characteristics of the motion alone and the sound effects that might accompany that motion. One type of sound effect is produced by a blast which generates a very loud noise at the source of the explosion. Such a blast is often regarded as severe and damaging even when damage did not occur and when motion was not perceptible. To the average layman, the loud noise itself is sufficient to prove severity. Similarly, a blast may be accompanied by an inaudible air wave that has sufficient energy to cause loose windows and doors to rattle. Motion may be imperceptible, but the building occupant can be expected to judge the intensity of the blast by what he heard. Simply stated, he thinks the building was subjected to strong vibrations because he heard the sounds of vibrating parts of the structure. He may be completely unaware that he actually felt no motion, and may conclude that the motion was severe. When the listener judges that the house was shaking violently, he often concludes that damage must have been done, and proceeds to examine the house carefully for some sign of the expected damage. Ground vibrations, independent of air waves, may also cause similar sound effects in a building, and even an experienced observer may be unable to say whether the creaks and rattles were the result of ground vibrations or air waves. These sound effects vary considerably from one structure to another. An old frame building with loose doors and loose, double-hung windows may be very noisy, whereas an adjacent masonry structure with tight doors and tight casement windows may not rattle at all. Thus, observers in these buildings probably would react quite differently to the same blast, even though the ground motion and structural motion at the two locations might be the same.

Normally, responses to the various blasts on a project will vary widely among individuals, and any blast, no matter how small or how remote, may bring on a damage claim. It would be ideal if blasting could be held at a level that no one would regard as potentially harmful. In a heavily populated area, this does not seem possible.

Another problem involved in dealing with observations of structures, especially if a long time interval is involved, is that other forces are at work on all structures, and cracks continue to appear and grow from causes other than blasting. Even in the absence of blasting, a 30-year-old building is expected to have more cracks than a 10-year-old building, which in turn is expected to have more cracks than a new building.

APPENDIX A

The following appendix is provided for the benefit of those readers who might like to have additional background information to develop a greater depth of understanding of some of the items previously discussed.

CRITERIA FOR DAMAGE TO RESIDENCES

The study of blasting effects on residences has been stimulated primarily because of the adverse responses of persons occupying buildings in the vicinity of blasting operations. Because such a response is common to nearly all persons, this adverse reaction has been taking place since the beginning of commercial blasting operations and has stimulated a great deal of investigation into the evaluation of blasting effects. The following comments provide a brief review of some of the publications and researches most often quoted in developing regulations, specifications, or other controls and limits.

ROCKWELL, 1927.

Following World War I, increased building demands in the U.S. brought about an expansion of the quarrying industry, requiring an increase in blasting activities in occupied areas. This activity stimulated an increasing number of blast damage claims and an increasing interest in the subject by technical investigators. One of the first reports on blasting effects reported in this country was made in 1927 by Rockwell (see reference list, Rockwell, 1927). Rockwell concluded that quarry blasting as normally conducted would not produce damage to residential structures if they were more than 200-300 feet from the quarry. It should be noted that there is a much wider choice of equipment and methods available to quarry operators today, so that same statement would not necessarily be true today, although generally so.

BUREAU OF MINES, 1942.

Growing complaints and litigations eventually stimulated a research effort headed by the Bureau of Mines to investigate the problem and to develop suitable criteria to avoid damage. The research continued through the 1930's, was completed in 1940, and led to the publication of Bulletin 442, in 1942 (Thoenen and Windes, 1942). Despite the adverse response to blasting, and the common damage claims associated with it, the Bureau investigators were unable to find damage generated by quarrying operations. This fact raised a difficulty in developing criteria, that is how to "prevent" something that wasn't happening. However, by designing and using mechanical shaking devices attached to various parts of houses, they were able to reach some conclusions about vibration damage to small structures, and offered to the public and the industry the first published recommendations to limit seismic effects. However, these recommendations quickly became obsolete as more representative case histories became documented through the work of Crandell and of subsequent researches.

CRANDELL, 1949.

In 1949, F. J. Crandell reported results from a study which involved actual damage to structures from blasting operations, in which observations were made of buildings shceduled for demolition that were subjected to high intensities of vibration before being demolished. In reporting his data, Crandell used a term called "Energy Ratio", which happens to be proportional to the square of particle velocity, the term most commonly used today to express the damage potential of blasting vibrations.

According to Crandell's vibration damage data, an Energy Ratio of 3.0 was safe (equivalent to a particle velocity of 3.3 inches per second), between 3.0 and 6.0 was a caution zone, and above 6.0 was a danger zone (equivalent to a particle velocity of 4.7 inches per second).

LANGEFORS ET AL, 1958.

In 1958, another report of damage studies appeared (Langefors, Kihlstrom and Westerberg, 1958). These investigators had obtained a large amount of data for blasting in hard rock at very close distances. Some damages occurred and were reported as follows:

2.8 in./sec.	No noticeable damage.
4.3 in./sec.	Fine cracking and fall of plaster.
6.3 in./sec.	Cracking.
9.1 in./sec.	Serious cracking.

EDWARDS AND NORTHWOOD, 1960.

In 1960, Edwards and Northwood reported a damage study on six residences. Three of the houses were located on a soft sand-clay material, and three were located on a well consolidated glacial till. Twenty two blasts were detonated at progressively smaller distances until damage occurred. The authors concluded that damage was more closely related to particle velocity than to displacement or acceleration, and that damage was likely to occur with a particle velocity of 4 to 5 inches per second. Including a factor of safety, they recommended a limit of 2.0 in./sec. to avoid damage.

VARIOUS STATES AND AGENCIES, 1949-1960.

Several states and organizations adopted vibration limits during this period from 1949 to 1960. For example, the State of Pennsylvania adopted 0.03 inches of displacement as a safe blasting limit. New Jersey and Massachusetts adopted an Energy Ratio of 1.0 (particle velocity of 1.92 in./sec.), based on Crandell's work, including a factor of safety. Agencies such as the U.S. Army Corps of Engineers and the New York State Power Authority specified a limit of an Energy Ratio = 1.0 for various construction projects.

BUREAU OF MINES, 1959-1972 - BULLETIN 656.

The U.S. Bureau of Mines also began a new seris of investigations, beginning in 1958. These culminated in the publication of a series of Reports of Investigations, and finally in the publication of Bulletin 656 in 1972 (Nicholls, Johnson and Duvall, 1972). Their report included a review of the major damage data from the previous studies mentioned above, and included data from an additional 171 blasts at 26 different sites. Their major conclusions were:

1. The damage potential relates more closely to particle velocity than to acceleration or displacement.

2. A limit of 2.0 in./sec. should not be exceeded for residences if the probability of threshold damage is to be kept low.

3. People are very sensitive to sound and vibration, and ground motions would have to be kept below 0.4 in./sec. if complaints and damage claims are to be kept low.

4. Air blast does not contribute to damage in most blasting operations. The control of ground vibration to safe levels automatically limits airblast overpressures to safe levels.

5. Regarding the delay intervals used in initiating sequential detonations, the report states that "the maximum charge weight per delay onsidered as the charge weight for each shot" an n

levels from blasts using 5 millisecond delays did not differ appreciably with those from shots with longer delays and were included in the analysis" (pg. 41).

BUREAU OF MINES, 1974-1980.

Many persons associated with the use of explosives were well aware that vibration levels of 2.0 in./sec. generated very strong adverse reactions from homeowners. Sounds of rattling and shaking, and the accompanying fear of property damage, generate strong public opposition at these levels. As a result, many quarry and mine operators have always kept vibration levels below this limit, even though it may have been permitted by regulation. However, in recent years, many of the regulatory agencies have become more sensitive to the public response and have imposed stricter limitations to reduce the fear of damage, often regarded as actual damage. For example, in 1957, the State of Pennsylvania had changed its regulation (from a displacement limit of 0.03 inches) to permit a particle velocity of 2.0 in./sec., but in 1974 adopted more stringent limits because of pressures from citizens groups.

The U.S. Bureau of Mines maintained an interest in different aspects of the general subject of blasting operations, including ground vibrations, airblast, and certain other topics not directly of interest to this case. From 1974, the Bureau undertook additional studies of ground vibrations and airblast. Several of their Reports of Investigations appeared in print in 1980. One of particular interest is RI 8507 (Siskind et al, 1980), primarily because it recommends a revision in criteria to more stringent levles, especially for low-frequency vibrations. In these recommendations, the previously suggested limit of 2.0 in./sec. was retained for high-frequency vibrations (above 40 Hz), but the suggested limit was reduced to 0.75 in./sec. for drywall construction and to 0.50 in./sec. for wet plaster construction in the frequency range of 4 to 12 Hz. Further, there is a suggestion for a displacement limit of 0.03 inches below 4 Hz, and of 0.008 inches between 12 and 40 Hz.

The authors point out that ordinary human activity inside a residence will often generate particle velocities of 0.5 in./sec. Thus, the effect of their more restrictive recommendations is to keep external ...es of vibration to the same damage potential as ...

activity.

RI 8507 is based largely on statistical and probability analyses of old data, including some which had been rejected previously by the Bureau of Mines authors of Bulletin 656 because of the questionable validity of some of the data. Relatively little new damage data was obtained. However, it is generally recognized that most light-weight frame residences do respond in the manner described in RI 8507, and that there is a greater potential for damage at the lower frequencies. This concept has been described in many earlier publications, including the Bureau Bulletins of 1942 and 1972. The theories behind this response have been discussed in publications for at least 100 years.

REFERENCES

PROJECT SPECIFICATIONS AND REGULATIONS

1942 - Thoenen and Windes, "Seismic Effects of Quarry Blasting" Bulletin 442, U.S. Bureau of Mines

1949 - Crandell, F. J., "Ground Vibrations Due to Blasting and Its Effect Upon Structures", Journal Boston Society of Civil Engineers, April, 1949

1958 - Langefors, Kihlstrom and Westerberg, "Ground Vibrations in Blasting", Water Power, February, 1958.

1960 - Edwards and Northwood, "Experimental Studies of the Effects of Blasting on Structures", The Engineer, Sept. 30, 1960.

1970 - Oriard, L. L., "Blasting Operations in the Urban Environment", AEG National Meeting, Washington, D.C., Bulletin, 1972.

1971 - Nicholls, Johnson and Duvall, "Blasting Vibrations and Their Effects on Structures", Bulletin 656, U.S. Bureau of Mines.

1972 - Hendron and Oriard, "Specifications for Controlled Blasting in Civil Engineering Projects", Proc. First North American Rapid Exc. and Tunneling Conference.

1974 - Wiss and Nicholls, "A Study of Damage to a Residential Structure from Blast Vibrations, ASCE, 1974.

1980 - Oriard and Coulson, "TVA Blast Vibration Criteria for Mass Concrete", ASCE National Meeting, Portland, Oregon, 1974.

1980 - Tart and Oriard, "Blast Damage Criteria for a Massive Concrete Structure", ASCE National Meeting, Portland, Oregon.

1980 - Siskind, Stagg, Kopp and Dowding, "Structure Response and Damage Produced by Ground Vibrations from Surface Mine Blasting", RI 8507, U. S. Bureau of Mines.

1982 - Oriard, L. L., "Blasting Effects and Their Control", Underground Mining Methods Handbook, SME of AIME, 1982.

PERSPECTIVE ON DAMAGE CRITERIA AND LEVELS OF DAMAGE

Previous comments in this report have been directed primarily to those studies and recommendations which have dealt with an effort to determine the greatest sensitivity of the poorest quality residences. The purpose of most of these studies has been directed to establishing criteria to prevent either threshold damage, or to prevent damage claims and complaints under the most unfavorable of conditions. Unfortunately, it is a common conclusion by many persons that any and all types of damage to structures might occur if vibrations exceed the conservative limits recommended. An experienced observer will realize that this is not the case at all. A more careful review of the available damage data will illustrate the fact that vibrations which exceed the "standard" recommendations do not normally cause damage, nor is such threshold damage of significance structurally. One illustration of this fact can be found in a study in 1969 in which the Bureau of Mines participated in a test program sponsored by the American Society of Civil Engineers (Wiss and Nichols, 1974). A 33-year-old residence was subjected to increasing levels of blast loading until damage finally occurred. A series of ten blasts was detonated near the residence. Through the first 8 blasts, the peak particle velocity had reached nearly 7 in./sec., but no damage occurred. The vibrations from test 9 opened 3 new cracks in gypsum wall board in an upstairs room after ground motion beside the house reached a peak particle velocity of 22.2 in./sec., over 11 times the "safe" levels recommended in Bulletin 656 and correspondingly higher than the more conservative limits suggested in RI 8507. There was no structural damage to the house, only the minor cosmetic damage in the gypsum wall board. In fact, the authors of the study report that variations in the widths of existing cracks were greater during intervals when blasting was not done than during periods when blasting occurred.

This writer has had many similar experiences. He has observed many residences and other small non-engineered buildings subjected to peak particle velocities in the range of 5 to 15 in./sec. without incurring damage of any kind. Although this writer has examined many hundreds of buildings before, during or after blasting operations, he has not yet had the experience of observing one where damage occurred below 2.0 in./sec. Such an occurrence must be considered unusual, not the norm.

These observations have not been limited to new, modern home construction. The writer has examined small residences (adobe, stone rubble, bamboo lath, filled-wall, etc.) in many parts of the world, including the United States, Canada, Mexico, Central America, South America, Europe, the Middle East, the Orient and the Pacific Islands. He has observed various construction methods, and the effects of various static and dynamic forces on these structures.

One case involving old buildings subjected to blasting took place in Monterey, California, when a large rock cut was excavated for a freeway between two of the oldest buildings in California, dating from the Spanish administration in the 1700's. These two old buildings were subjected to blasting vibrations with peak particle velocities of the order of 2.3 in./sec. and did not sustain even threshold damage, despite their deteriorated condition. (see Photo) (one is adobe).

Much higher vibration intensities were received by approximately 100 homes in a small town on another occasion when blasting approached within just a few feet. The blasting operations generated peak particle velocities in the range of 5 to 30 in./sec. at the nearest portions of many of these buildings. No building damages were reported or observed (see Photos).

VIBRATIONS INDUCED BY BUILDING OCCUPANTS AND NEARBY TRAFFIC

Technical investigators have long been aware of the deceptive nature of blasting vibrations because of the sound effects that accompany them. Observers tend to have an exaggerated perception of blasting. In order to provide comparative data, the Bureau of Mines and others have measured the vibrations induced by other activities. A few examples appear in the literature.

Bulletin 442 of the Bureau of Mines (1942) reports several sources of vibration in addition to blasting. A brief summary is given below. For more details, the reader is referred to the Bulletin.

14,000 lb. truck, solid tires: (at 63 ft.)	0.0069 in. (displacement)
8,500 lb. truck, pneumatic tires: (63 ft.)	0.0026 in.
motor vibration:	0.0019 in.
man jumping a few inches:	0.0068 in.
blasting, 1.13 pounds explosive. (715 ft.)	0.00015 in.
blasting, 17,250 lbs. explosive.(1810 ft.)	0.033 in.

Of eleven quarry tests, only two gave more displacement than the heavy truck.

Bulletin 656 of the Bureau of Mines (1972) gives additional data of similar character.

walking:	0.37 in./sec.
door closing:	0.06 in./sec.
jumping:	5.0 in./sec.
heel drops (rising on toes and dropping back on heels):	3.5 in./sec.

Report of Investigations 8507 reports the following:

walking:	1.49 in./sec.
nail hammering:	3.81 in./sec.
sliding glass door:	0.27 in./sec.
slamming entrance door:	1.29 in./sec.
heel drops:	5.84 in./sec.
jumping:	10.1 in./sec.
mine blasts:	1.37 in./sec.

An experienced technical investigator is well aware that typical blasting vibrations, generated by controlled operations at moderate-

rge distances do not generate more vibration tha activities, although this fact has not generally been perceived by the public. In fact, it goes contrary to common intuition, and is commonly rejected out-of-hand as being untrue by most untrained persons. Many persons will riducule such statements as being biased and untrue, even when the data is available to prove the validity.

TIME CORRELATIONS BETWEEN DAMAGE, BLASTING AND OTHER CAUSES

The average person has had no reason to study structures nor the earth sciences, and is not aware of the various forces which act in silence on a structure, causing it to deteriorate with time. Proof of the lack of awareness of these forces is the frequency with which the average person asks the question, "If it wasn't blasting which caused these cracks, what could it have been?" This is one of the most overworked questions heard in explosives engineering. Yet, the fact that such a question could be asked demonstrates how formidable is the task of public education on this topic. Of course, there is a long list of factors besides blasting "that it could have been".

The above question is usually raised because of some apparent time correlation between blasting activity and the building crack (or other defect). There is no doubt that an apparent time correlation has a strong psyochological impact on a person's judgment. However, many forces are usually involved and the static forces are not usually recognized.

The commonly held conclusion is that one needs only to make an inspection of the structure in question before and after the blasting project. If the conditions are different at the time of the latest inspection, it is assumed that any observed change was the result of stressed induced by the blasting, unless it is recognizably impossible to relate the damage to vibration. Unfortunately, there can be considerable differences of opinion as to what is recognizably impossible. Claims files are full of items that the majority of technical consultants are aware could not be correlated with vibrations. Yet, some persons will accept allegations of this type if the feature of interest seems to have developed during the time period in question. Of course, such conclusions are reinforced if the "damage" seems to be the kind of effect that could be generated by vibrations of sufficient intensity. The most common of these are building cracks of various types. But merely because it is possible to generate cracks by vibrations does not mean that cracks which occur during the time of blasting operations have any relationship whatever to the blasting.

The most dramatic type of case is that where older homes in relatively good condition then undergo damage during a relatively short period of time during which blasting is taking place. But even in that case, time correlation, or apparent time correlation, may be quite deceptive and irrelevant. If there is not sufficient intensity of vibration to account for the damage, it clearly must be caused by something else, even though the cause may not be immediately obvious. This can be illustrated by reference to a case history, where this writer was retained by the administration of a small city to investigate extensive residential damages in the general vicinity of a quarrying operation. Many homes were damaged and some of the damage was quite serious. It was well documented that much of this damage had occurred within a period of about a year to homes that were about 25 to 30 years old at the time. These houses were about a mile from the quarrying operation. The quarry had been operating intermittently for many years. It had been idle for some time, but undertook blasting operations for a portion of the year in question. There was documented evidence that a considerable amount of damage occurred during the time of the blasting operations.

Virtually every home owner who had suffered any damage was firmly convinced that the quarrying operations were to blame. However, certain important facts were noted during the investigation that did not support this conclusion. For example, houses with no damage at all were found next door to houses that had suffered very serious damage. Also, another housing development in the opposite direction was located directly in front of the quarry at very close distance, yet none of these houses had suffered any damage at all. Calculations showed that the amount of vibration at the area in question could not be capable of causing damage. The only "proof" of damage from blasting was that they both took place during the same period of time. Of course, everyone asked the same question, "What else could have caused the damage? Obviously, it must have been blasting."

It turned out that hundreds of homes in this general region had suffered damage during this period of time, some of them many miles from the small quarry. It happened during a period of extremely dry weather. This one residential area was built on a fill where the water table normally was found very close to the ground surface. During this dry weather, the water table dropped, the soils dried out, shrunk and settled. There was as much as 6 inches difference in soil settlement between the front and back of some houses.

There were additional facts disclosed by the investigation. In all, it was clear to an experienced technical investigator that there was no correlation between the blasting activities and the extensive damage in this residential area despite the universal opinion of the homewowners to the contrary. Once the technical facts were made known to the city administration, the case was immediately closed.

Static Forces

Of course, there are many static (non-vibratory) forces which act on buildings to generate cracks and other defects. These may be generated either internally or from external sources. Many internal stresses are developed by changes in moisture and temperature, seasoning of lumber, drying and curing of plaster, concrete or adobe, changes in application of internal heat, aging, loss of Coulomb friction, changes in external soil conditions, drainage, weather, vegetation, etc., as well as the gravitational loads induced by the weight of the structure itself and all of the dead loads added by furnishings and persons inside the home.

The more common dynamic stresses are induced by human activity within the home and wind pressures against the exterior surfaces of the building, although others may be found in certain homes in the vicinity of industrial activities, etc. Of course, earthquake vibrations would be a matter of interest in seismically active areas.

As in the case history described above, expansive soils are one of the most serious problems for small buildings, especially those that are not engineered. It has been estimated that such soils inflict at least $2.3 billion in damage to buildings, roads, pipelines and other structures each year. Damage due to expansive soils results from shrinking and swelling of the soil in response to changes in the moisture content. The moisture changes may occur naturally, or may be influenced further by the landscaping and yard maintenance practices of the building occupant.

Mathewson et al (1980) provide a description of a study of over 400 brick veneer, single-family homes located in three cities in Texas, in which the authors investigated the effects of expansive soils on building damage. Sixteen independent variables were evaluated. A few of the more important included:

1. Age.

2. Vegetation (amount and distance from house).
3. Depth of the active soil zone.
4. Rainfall ratio.
5. Plasticity index.
6. Yard maintenance.

Because of the southern location, it was not necessary to consider the additional influence of freezing and thawing, a problem in most areas in the continental U.S.

The displacement associated with the blasting operations in Paguate appeared to range from less than 0.0001 inch (one ten thousandth of an inch) to as much as 0.01 to 0.02 inches (one to two hundredths of an inch). In contrast, there are many natural strains of greater magnitude to which houses are subjected. For example, shrinkage or expansion of wooden timbers frequently causes changes in dimension of the order of 1/4 to 1.0 inch, as moisture content changes from season to season. Also, all materials are subjected to changes in dimension from changes in temperature, as well as moisture, and each material has its own characteristic coefficient of expansion. Thus, not only do these materials undergo stresses, but adjacent materials undergo different changes and this difference causes very high stresses where the materials meet.

Water is commonly employed in the preparation of certain building materials, such as concrete, plaster, stucco and adobe. When these materials cure and dry, the water is evaporated, and there is a change in the volume (dimensions) of the material. A poorly formulated adobe can change volume by as much as 1/3 of the original.

Architects, engineers, and most experienced builders are aware that there are many natural causes of cracks in buildings. As early as 1925, one could find publications tabulating some of the common causes of cracks. The Architect's Small House Service Bureau of the United States published a list of 40 reasons why walls and ceilings crack (The Small Home, Vol. 4, No. 8, 1925).

A careful study of buildings shows that many cracks not only appear and grow larger as the building gets older, but that some cracks expand and contract on a relatively short-term basis with changes in temperature and moisture. In one case, this writer measured small changes in the widths of cracks between morning and afternoon (due to temperature changes) in a plaster applied over a new type of insulation.

In order to develop those same strains by vibration, it would be necessary to generate vibrations that would seem catastrophic to occupants of a building. For example, refer to the section of this report titled "Perspective on Damage Criteria and Levels of Damage". Here, there is mention of the damage study jointly conducted by the Bureau of Mines and American Society of Civil Engineers, where an old home was subjected to vibrations intensities up to 22.2 in./sec. The study report states that variations in the widths of existing cracks were greater during intervals when blasting was not done than during periods when blasting occurred.

APPENDIX B

PHOTOGRAPHS

The following photographs were selected as being representative examples of the types of conditions found in Paguate, in neighboring villages, and in other areas in New Mexico. In addition, the appendix contains some photographs illustrating blasting operations taking place directly adjacent to various types of buildings where excavation had to be conducted in other rocky regions of the country.

PHOTOGRAPHS OF PAGUATE

The following 12 photographs show typical building conditions in Paguate for a variety of types of construction.

In general, the photos begin closest to the mining operations and proceed to greater distances.

The last two photos show the interior of an adobe structure on the mining property.

PHOTOGRAPHS OF WEST ALBUQUERQUE

A visitor to Albuquerque would note that the same types of cracks and deterioration that were found in Paguate and neighboring villages can be seen everywhere, whether for residential or commercial construction.

The following six photos show typical cracks as seen in commercial buildings in West Albuquerque.

PHOTOGRAPHS OF BURNHAM

The following twelve photographs show buildings in Burnham, New Mexico. The reader will see the same conditions that have been noted in the preceding photographs in Paguate and other areas.

The following photographs were taken to document the conditions of residences in advance of the beginning of blasting operations in that area. Such conditions are common everywhere, but they are often overlooked until brought to the attention of the occupants.

PHOTOGRAPHS OF BLASTING CLOSE TO BUILDINGS

The following ten photographs were selected to illustrate the fact that blasting must often take place very close to existing buildings when construction work must be done in rock regions. The photographs were taken at different times and at different locations.

No damage was done to any of the buildings seen in these photos.

The first photo shows a deep rock cut which was blasted between two of the oldest buildings in California, dating from the Spanish adminstration. One of these was an old adobe structure.

In every case shown here, the vibration intensities greatly exceeded those transmitted to Paguate.

PROFESSIONAL RESUME OF THE AUTHOR

Lewis L. Oriard